Understanding the Possible Proton Antiproton Bound State Observed by BES Collaboration

Chong-Shou Gao and Shi-Lin Zhu
Department of Physics, Peking University, Beijing 100871, China

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Abstract

We comment on the quantum numbers and decay channels of the possible proton antiproton bound state observed by BES Collaboration. Based on the general symmetry consideration and available experimental information, we conclude that the quantum number of this state is very likely to be $J^{PC} = 0^{-+}, I^G = 0^+$, which can not decay into final states $\pi^+\pi^-, 2\pi^0, K\bar{K}, 3\pi$. Besides its dissociation into $p\bar{p}$, the other important mesonic decay modes could be $\eta\pi\pi$, $\eta'\pi\pi$, $\eta\eta\eta$, 4π, $K\bar{K}\pi$, $\eta K\bar{K}$, $K\bar{K}\pi\pi$, 6π. Experimental search of this signal in these meson final states is strongly called for.

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Recently BES Collaboration in Beijing announced that they observed a narrow enhancement near the threshold in the invariant mass spectrum of $p\bar{p}$ pairs from $J/\psi \to \gamma p\bar{p}$ radiative decays. No similar structure is found in the $\pi^0 p\bar{p}$ channel [1].

If the near threshold enhancement is fit with S-wave Breit-Wigner resonance function, the resulting peak mass is $M = 1859^{+3}_{-10}(\text{stat})^{+5}_{-25}(\text{sys})$ MeV below $2m_p$. The total width is less than 30 MeV. Clearly such a mass and width does not match that of any known particle in PDG [6]. With a P-wave fit, the peak mass is very close to the threshold, $M = 1876.4 \pm 0.9$ MeV and the total width is very narrow, $\Gamma = 4.6 \pm 1.8$ MeV. D-wave fit failed badly [1]. The photon polar angle distribution is consistent with $1 + \cos^2\theta_\gamma$ which suggests the angular momentum is very likely to be $J = 0$.

The study of the possible nucleon anti-nucleon bound state has a very long history. An extensive and excellent review is given in Ref. [2]. Interested readers are referred to Refs. [2, 3] for the general status of the experiments and various theoretical approaches using quark model or conventional nucleon potentials. Datta and O'Donnell described the narrow resonance in the decay $J/\psi \to \gamma p\bar{p}$ deuteron-like singlet state in a simple potential model with a $\lambda \cdot \lambda$ confining interaction [4]. Very recently Rosner discussed the nature of the low-mass baryon-antibaryon enhancement observed in B meson decays [5].

In this short note we will try to understand the quantum number of this state making full use of general symmetry requirement and the available experimental information.

We will also discuss the experimental search of this state in the possible mesonic decay channels.

Both Quantum Chromodynamics (QCD) and Quantum Electrodynamics (QED) conserve the charge conjugation parity. Both photon and J/Ψ have $J^{PC} = 1^{--}$. So C-parity of this state is positive $C = +$. For the particle and antiparticle system, we know from textbooks that $C = (-)^{L+S}$. Positive C-parity requires $L + S = 2m$ where m is an integer. The spin of proton is $\frac{1}{2}$. So the total spin of this state is $S = 0, 1$. The parity is $P = (-)^{L+1}$. BES measurement suggests that the total angular momentum is $J = 0$ or $J = 1$. When $L = S = 0$, this state has $J^{PC} = 0^{-+}$. The combination of $L = 2, S = 0$ will lead to $J = 2$ which is already excluded by BES measurement since a D-wave fit yields unacceptable χ^2. When $L = S = 1$, the angular momentum could be $J = 0, 1, 2$. So, in principle, the quantum number of this state can be $J^{PC} = 1^{++}, 0^{++}$ with $L = S = 1$ or $J^{PC} = 0^{-+}$ with $L = S = 0$. BES's measurement of photon polar angle distribution favors $J = 0$. From now on, we mainly discuss the possibility of $J^{PC} = 0^{-+}, 0^{++}$.

Now let us move on to the isospin and G-parity. The production mechanism of possible $p\bar{p}$ bound state is not unique in the radiative decay $J/\Psi \to \gamma p\bar{p}$. For example the photon can be produced when charm quark pairs annihilate in the reaction $J/\Psi \to ng + \gamma \to 3q + 3\bar{q} + \gamma \to p\bar{p} + \gamma$ where g is the virtual gluon, $n = 2, 4, \cdots$ is the number of virtual gluons and $q(\bar{q})$ is the quark (antiquark) field. The photon was emitted from the internal charm quark lines. The n gluons hadronize into three quark and anti-quark pairs. So the isospin of the resulting $p\bar{p}$ system should be zero. If perturbative QCD is still applicable in this energy scale, the leading order cross section is $\sim \mathcal{O}(\alpha_s^4\alpha)$ where α_s and α is the strong and electromagnetic coupling constants respectively.

The other production mechanism is as follows : $J/\Psi \to ng \to 3q + 3\bar{q} \to 3q + 3\bar{q} + \gamma \to p\bar{p} + \gamma$, where $n = 3, 5, \cdots$. The J/Ψ first annihilates into three or more virtual gluons which turn into three up/down quark and anti-quark pairs. Note the isospin of the system of the three pairs of light quark and anti-quark is zero. Then a real photon is emitted from one of the up or down quarks. QED violates isospin symmetry explicitly. The isospin of the photon can be either one or zero. After hadronization, the isospin of the final $p\bar{p}$ system can be either one or zero. The leading order cross section is $\sim \mathcal{O}(\alpha_s^6\alpha)$, which is suppressed by α_s^2 compared with that of the first process.

Right now we know very little of the dynamics of this $p\bar{p}$ state. In the extreme case, it could be a baryonium or molecule state of proton and antiproton bound by long-range strong force or by electromagnetic force or by a combination of these two forces. Or it could be a six-quark state composed of three quarks and three antiquarks. We believe that this $p\bar{p}$ state is an isoscalar to a very good accuracy. However, we also discuss the possibility of it being an isovector for the sake of completeness. Later we will show such a possibility is already excluded by very recent BES analysis. Let us assume this state can have $I^G = 0^+$ or 1^- first.

Now we have four possibilities of the quantum number of this state: $J^{PC}I^G = 0^{++}1^-$, $0^{++}0^+$, $0^{-+}1^-$, $0^{-+}0^+$. We shall discuss the possible mesonic decay channels of this state according to different quantum numbers.

For the strong decays of this state, the conservation of angular momentum, parity, C-parity, isospin, G-parity, charge and four momentum constrains the possible final states

greatly even if we know nothing about how this state is bound. If its quantum number is $J^{PC}I^G = 0^{++}1^-$, the symmetry consideration allows the following possible meson final states [7]: $\pi^0\eta$, $\pi^0\eta'$, $K\bar{K}$, $2\pi(K\bar{K})$, $\eta\pi(K\bar{K})$, $\eta\eta(K\bar{K})$, 5π etc. We limit ourselves to final states less than six particles. Final states with particle number greater than five will be too challenging for BES detector. The dominant mesonic decay modes are possibly $K\bar{K}$, $\pi^0\eta$, $\pi^0\eta'$.

With $J^{PC}I^G = 0^{++}0^+$, the possible meson final states are: $\pi\pi$, $K\bar{K}$, $\eta\eta$, $\eta\eta'$, $\eta'\eta'$, 4π, $\eta\pi(K\bar{K})$, $\eta\eta(K\bar{K})$, $2\pi(K\bar{K})$ etc. The dominant mesonic decay modes are possibly $\pi\pi, K\bar{K}, 4\pi$.

With $J^{PC}I^G = 0^{-+}1^-$, the possible meson final states are: 3π, $\rho\pi$, $f_0\pi$, $f_0(1370)\pi$, $a_0\eta$, $f_0(1500)\pi$, $\eta\eta\pi$, $\eta\eta'\pi$ etc. The dominant mesonic decay mode is possibly 3π.

Very recently BES Collaboration have performed careful search of this state in the radiative decay channels other than $\gamma p\bar{p}$. No evidence of a possible bound state near the threshold is found in the two pions, three pions, and two kaons final states in the decays $J/\Psi \to \gamma 2\pi$, $J/\Psi \to \gamma 3\pi$ and $J/\Psi \to \gamma K\bar{K}$ [8].

We believe that BES detector should be able to observe this possible $p\bar{p}$ bound state through the radiative two-pion, three-pion and two-kaon decay channels if its quantum number were $J^{PC}I^G = 0^{++}1^-, 0^{++}0^+, 0^{-+}1^-$. Since BES has not seen a clear signal in the 2π, 3π, and $K\bar{K}$ decay channels, we conclude that the quantum number of the possible bound state observed by BES Collaboration is very likely to be $J^{PC}I^G = 0^{-+}0^+$. Such a quantum number is consistent with BES's S-wave fit.

From now on we focus on the decay patterns of possible $p\bar{p}$ bound state with $J^{PC}I^G = 0^{-+}0^+$. Parity and angular momentum conservation forbids any state with such a quantum number decaying into two pions and two kaons. G-parity conservation forbids it decaying into three pions. The smaller the total number of the necessary partial waves $\mathcal{L} = \Sigma l_i$, the bigger the partial decay width as one naively expects because of phase space suppression. We list below the possible final states according to the total partial wave number $\mathcal{L}$. For $\mathcal{L} = 0$, the possible decay modes are $K^+K^-\pi^0$, $K_SK_S\pi^0$, $K_LK_L\pi^0$, $K^+\bar{K}^0\pi^-$, $K^-K^0\pi^+$, ηK^+K^-, ηK_SK_S, ηK_LK_L, $\eta\pi^+\pi^-$, $\eta\pi^0\pi^0$, $\eta'\pi^+\pi^-$, $\eta'\pi^0\pi^0$, $\eta\eta\eta$ [7].

For $\mathcal{L} = 3$, the possible decay modes are $K^+K^-\pi^+\pi^-$, $K_LK_S\pi^+\pi^-$, $K^+\bar{K}^0\pi^-\pi^0$, $K^-K^0\pi^+\pi^0$. For $\mathcal{L} = 5$, the possible decay modes are $\pi^+\pi^+\pi^-\pi^-$, $\pi^+\pi^-\pi^0\pi^0$, $K^+K^-\pi^0\pi^0$, $K_SK_S\pi^+\pi^-$, $K_SK_S\pi^0\pi^0$, $K_LK_L\pi^+\pi^-$, $K_LK_L\pi^0\pi^0$, $\eta\pi^0K^+K^-$, $\eta\pi^0K_SK_S$, $\eta\pi^+K^-K^0$, $\eta\pi^-K^+\bar{K}^0$, $\eta\pi^0K_LK_L$. There is also the possible final state $\pi^0\pi^0\pi^0\pi^0$ with $\mathcal{L} = 9$.

The absence of strange quarks inside this $p\bar{p}$ bound state may render the partial width of $K\bar{K}\pi$ channels smaller than that of $\eta\pi\pi$ if the decay happens through the regrouping of the quark and antiquarks inside the proton and antiproton instead of through quark antiquark annihilation. If selection rule allows, the three pairs of light quark and antiquark may recombine with each other to form three color singlets easily, which eventually decay into three mesons. One, or two or all of the resulting three mesons may decay into lighter meson final states like multiple pions if symmetry allows.

OBELIX Collaboration observed that $p\bar{p} \to K^+K^-$ cross section is much smaller than that of $p\bar{p} \to \pi^+\pi^-$ at very low momenta around 50 MeV [9]. In fact the total $p\bar{p}$ annihilation cross section is dominated by the multipion channels like $3\pi, 4\pi, 5\pi$. Especially the cross section of the 5π channel is three times larger than that of $3\pi, 4\pi$ channels at 43.6

MeV [9].

We eagerly call for BES experimentalists to make strong efforts to search for this very interesting state in the above listed final states, especially with smaller $\mathcal{L}$. Confirmation of the existence of this state in the meson final states will help unveil the mysterious underlying dynamics of this multiquark system, thus deepen our knowledge of the low energy sector of QCD.

Finally, we note in passing that although BES measurement of the photon polar angle distribution favors $J = 0$, the possibility of $J = 1$ is not absolutely excluded yet. If this state has $J^{PC}I^G = 1^{++}1^-$, it can decay into $(\rho\pi)_{\text{S-wave}}$, $(\rho\pi)_{\text{D-wave}}$, $f_0(980)\pi$ etc. The absence of clear signal in the three-pion final states has excluded such quantum number assignment.

With $J^{PC}I^G = 1^{++}0^+$, the possible final states with the lowest total partial wave number $\mathcal{L} = 1$ are $K^+K^-\pi^0$, $K_LK_L\pi^0$, $K_SK_S\pi^0$, $K^+\bar{K}^0\pi^-$, $K^-K^0\pi^+$, $\eta\pi^0\pi^0$, ηK^+K^-, ηK_SK_S, ηK_LK_L. We do not list the possible final states with $\mathcal{L} = 2, 4, 6$ here. Interested readers may consult Ref. [7] or PDG [6].

In the extreme case that no narrow resonance with $J^{PC}I^G = 0^{-+}0^+$ is observed in the above mesonic decay channels, it is worthwhile making some efforts to look for possible $p\bar{p}$ resonances with $J^{PC}I^G = 1^{++}0^+$ in the mesonic final states.

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